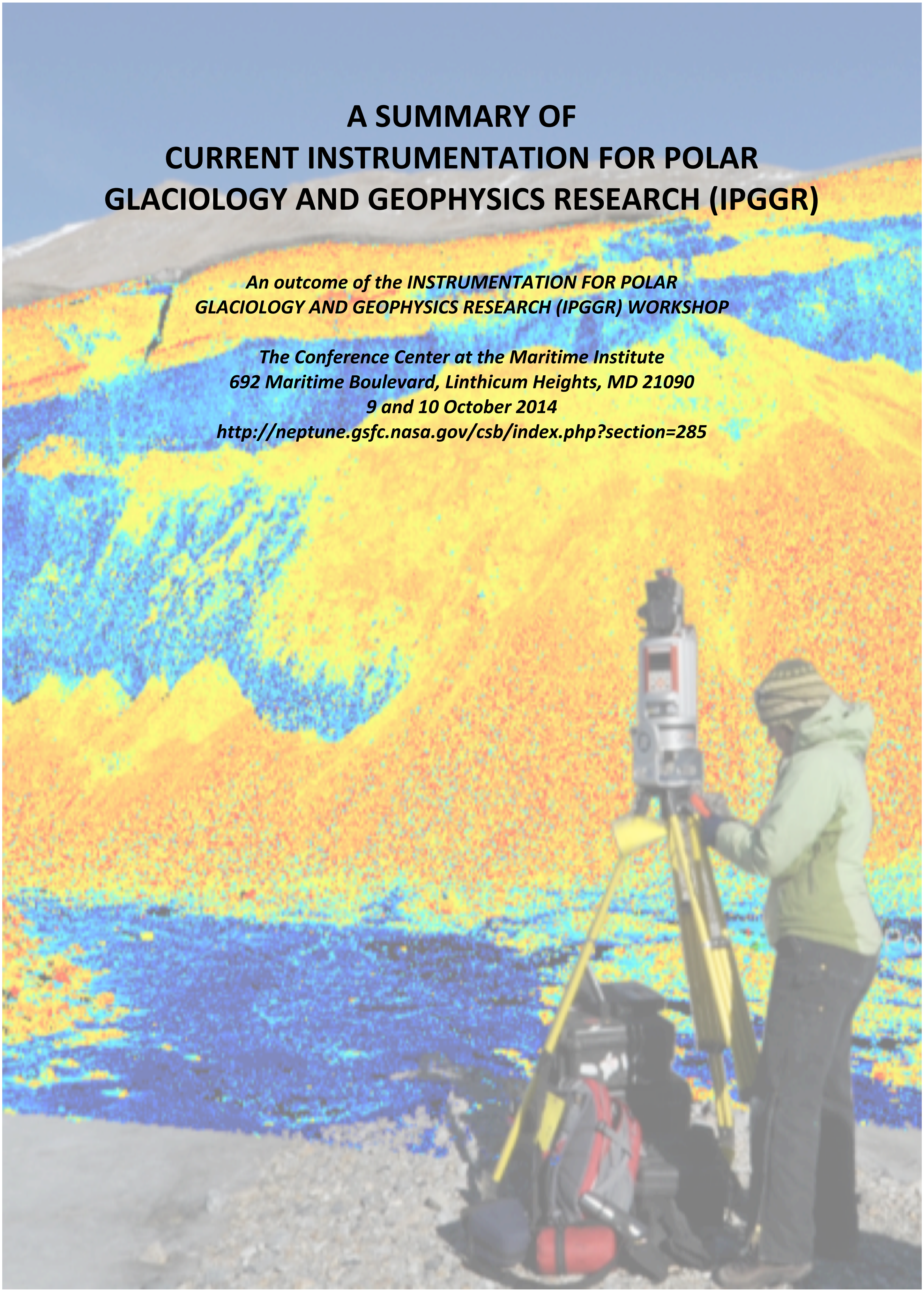
A SUMMARY OF CURRENT INSTRUMENTATION FOR POLAR GLACIOLOGY AND GEOPHYSICS RESEARCH (IPGGR)

An outcome of the INSTRUMENTATION FOR POLAR GLACIOLOGY AND GEOPHYSICS RESEARCH (IPGGR) WORKSHOP

The Conference Center at the Maritime Institute
692 Maritime Boulevard, Linthicum Heights, MD 21090
9 and 10 October 2014
http://neptune.gsfc.nasa.gov/csb/index.php?section=285



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Kelly Brunt	Co-Convener, ESSIC, University of Maryland; NASA GSFC Cryosphere
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Carlton Leuschen	Steering Committee, University Kansas
Duncan Young	Steering Committee, University of Texas, Institute for Geophysics
Kirsteen Tinto	Steering Committee, Lamont-Doherty Earth Observatory
Knut Christianson	Steering Committee, NYU, Courant Institute of Mathematical Sciences
Marianne Okal	Steering Committee, UNAVCO

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SUMMARY

This document summarizes the technologies presented at the Instrumentation for Polar Glaciology and Geophysics Research (IPGGR) Workshop, was held 9–10 October 2014, in Baltimore, Maryland. Details of that workshop can be found at the workshop website, which is hosted by NASA Cryospheric Sciences Laboratory, and includes the participant list, agenda, a workshop report, and this instrument summary document (http://neptune.gsfc.nasa.gov/csb/index.php?section=285).

Discussions during the workshop included methods of updating this document as technologies evolve. A regular poster session that focuses on instrumentation for polar research should be convened at the AGU Fall Meeting. Input from the conference session could be appended to this document.

1) Ground-based instrumentation

Global positioning system (GPS)

A community pool of global positioning system (GPS) instruments for polar field-based applications is available through UNAVCO, an NSF-funded, independent, non-profit university consortium. Surveys are generally campaign-style (cm-accuracy) or intended for long-term-monitoring (mm-accuracy).

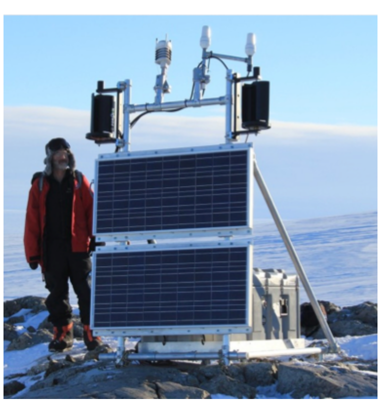
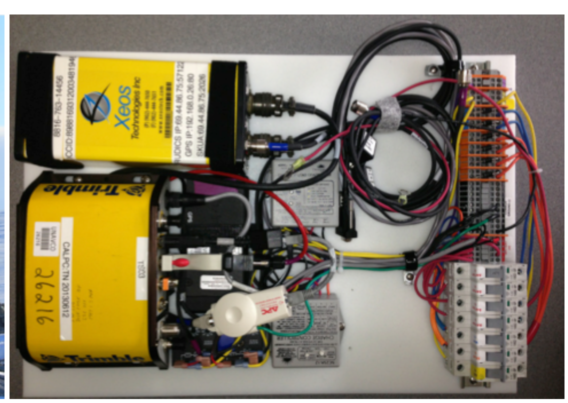
Applications:
Ice motion; tidal flexure of ice shelves; tectonics; ionosphere; surface elevation profiles/changes; snow depth.

Field:
UNAVCO Polar Services provides instrumentation, instrument training, and technical support for field-based researchers. Their autonomous field stations in the Arctic and Antarctic can provide continuous operation and data telemetry. However, power requirements are considered one of the main limitations of this technology.

Data processing and access:
UNAVCO provides support for access to GPS processing software; further, consistent with UNAVCO's Data Policy, they provide a free and open data archive service, most notably through their Data Archive Interface (http://www.unavco.org/data/data.html).

Contact:
Joseph Pettit, UNAVCO, Polar Services Manager (pettit@unavco.org):
http://www.unavco.org/projects/project-support/polar/polar.html

Beem, Tulaczyk, King, Bougamont, Fricker, & Christoffersen (2014). Variable deceleration of Whillans Ice Stream, West Antarctica. Journal of Geophysical Research: Earth Surface, 119(2), 212-224.
Lucas Beem, California Institute of Technology (lhbeem@gmail.com)



(Photos: Pettit)

Terrestrial laser scanning (TLS)

A community pool of terrestrial laser scanning (TLS) platforms for polar field-based applications is available through UNAVCO, an NSF-funded, independent, non-profit university consortium. UNAVCO instruments are generally in the near-IR (1550 nm), which is typically eye-safe, but has weaker returns on snow and ice; however, one unit is available in green (532 nm), which has better reflectivity on snow and ice but is less eye-safe and whose range is limited to ~100 m. Scanners have a 100 m – 2 km range and collect at 70 kHz to 1 MHz rates. They can achieve 5–8 mm accuracy and 3–5 mm precision.

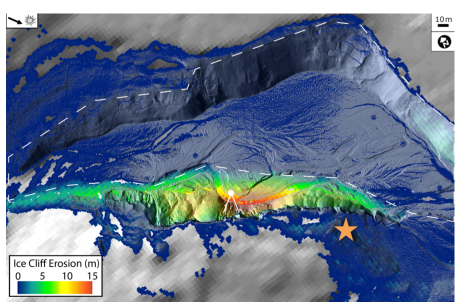
Applications:
High-resolution, georeferenced mapping (DEM creation); multi-year change detection; surface modelling; volumetric calculations.

Field:
UNAVCO Polar Services provides instrumentation, training, and technical support for field-based researchers.

Data processing and access:
This is an emerging field. Processing of these datasets has become easier. Datasets are large and formats are only recently becoming standardized. Consistent with UNAVCO's Data Policy, they provide free and open access to the TLS Field Project Archive (http://tls.unavco.org/repository). UNAVCO also provides software access to several TLS software packages (RiSCAN Pro, Cyclone, QT Modeler, BM Geographic Calculator, etc.).

*Contact:*Marianne Okal, UNAVCO, TLS Data Engineer (okal@unavco.org):
http://www.unavco.org/projects/project-support/tls-support/tls-support.html

Levy, Fountain, Dickson, Head, Okal, Marchant, & Watters (2013). Accelerated thermokarst formation in the McMurdo Dry Valleys, Antarctica. Scientific Reports, 3.
Joe Levy, University of Texas, Institute for Geophysics (jlevy@ig.utexas.edu)



(Photos: Okal, Levy)

Passive source seismology, intermediate and broadband seismometers

A community pool of broadband and intermediate seismometers for polar field-based applications is available through PASSCAL, an NSF-funded instrument center. PASSCAL provides sensors, data-loggers, and power systems for polar deployments; these systems can operate continuously, year-round. PASSCAL has made advances in reducing the weight of the systems by optimizing power configurations, but the telemetry of the large datasets remains impossible and is a limitation for this technology.

Applications:
Iceberg calving; fracturing; basal sliding; ocean tides; tectonics; global seismology.

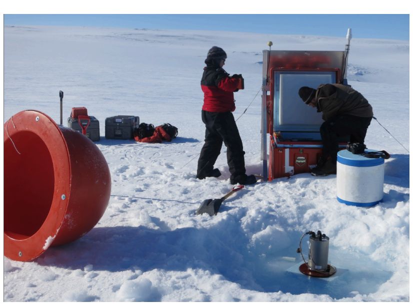
Field:
PASSCAL Polar Programs provides seismometers, training, and technical support for field-based researchers.

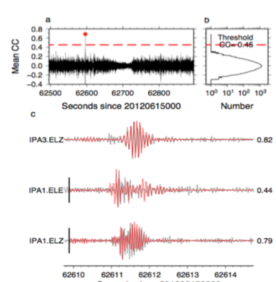
Data processing and access:
Users need a trained seismologist to analyze time series before it can be interpreted. Consistent with IRIS/PASSCAL's Data Delivery Policy, access to data collected with their instruments, in SEED format, is available at their data access site (http://www.iris.edu/data/sources.htm).

Contact:
IRIS PASSCAL, Polar (http://www.passcal.nmt.edu/content/polar)

Winberry, Anandakrishnan, Wiens, & Alley (2013). Nucleation and seismic tremor associated with the glacial earthquakes of Whillans Ice Stream, Antarctica. Geophysical Research Letters, 40(2), 312-315.
Paul Winberry, Central Washington University (paul.winberry@gmail.com)

Walter, Brodsky, Tulaczyk, Schwartz, & Pettersson (2011). Transient slip events from near-field seismic and geodetic data on a glacier fault, Whillans Ice Plain, West Antarctica. Journal of Geophysical Research, 116, F01021.
Jake Walter, University of Texas, Institute for Geophysics (jwalter@ig.utexas.edu)





(Photos: Winberry & Walter)

Active source seismology and short-period seismometers

Use of active source seismology for polar field-based applications has occurred since the 1950's. Today, a community pool of short-period seismometers for polar applications is available through PASSCAL, an NSF-funded instrument center. PASSCAL provides sensors, data-loggers, and power systems for polar deployments. PASSCAL has made advances in reducing the weight of the systems by optimizing power configurations. Seismic sources range from sledgehammers to a truck-mounted vibrator seismic source.

Applications:
Basal hydrology; basal stratigraphy, structure; ice thickness; ice temperature and fabric.

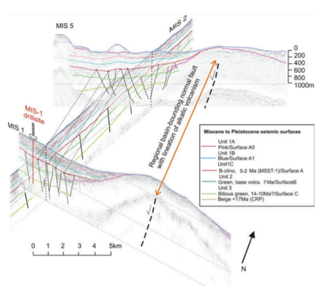
Field:
PASSCAL Polar Programs provides seismometers, training, and technical support for field-based researchers. A truck-mounted vibrator seismic source (vibroseis) has been tested in Antarctica; however, that equipment is not part of the community resource pool.

Data processing and access:
Consistent with IRIS/PASSCAL's Data Delivery Policy, access to data collected with their instruments, in PH5 or SEG-Y format, is available at their data access site (http://www.iris.edu/data/sources.htm).

Contact:
IRIS PASSCAL, Polar (http://www.passcal.nmt.edu/content/polar)

Anandakrishnan, Blankenship, Alley, & Stoffa (1998). Influence of subglacial geology on the position of a West Antarctic ice stream from seismic observations. Nature, 394(6688), 62-65.
Sridhar Anandakrishnan, Pennsylvania State University (sak@essc.psu.edu)

Speece, Luyendyk, Harwood, Powell, Wilson, Pekar, Tulaczyk, & Rack (2013). A sled-mounted vibroseis seismic source for geological studies in Antarctica. In AGU Fall Meeting Abstracts.
Marvin Speece, Montana Tech (mspeece@mtech.edu)



(Photos: Speece)

Terrestrial radar interferometry (TRI)

Use of terrestrial radar interferometry (TRI) for polar field-based applications has been limited so far. This technology has been used to investigate topographic change, ice velocity, tides, and currents. Scanners have a 15-km range and are generally in the Ku-band and have a range resolution of 1 m.

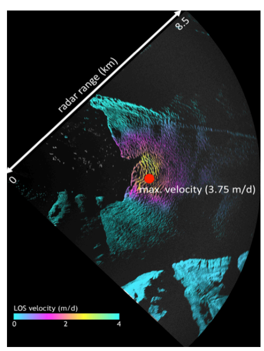
Applications:
Ice motion; and ice-ocean interaction at marine interface.

Field:
TRI has been used in other areas of Earth science research; use of TRI for polar research is emerging. Instrumentation is limited.

Data processing and access:
This is an emerging field. Processing is unique to the application. Archiving and access to TRI data is anticipated to be through UNAVCO, similar to TLS data.

Contact:
Tim Dixon, University of South Florida, Tampa (thd@usf.edu)

Voytenko, Dixon, Howat, Gourmelen, Lembke, Werner, de la Pena, & Oddsson, (2014). Multi-year observations of Breiðamerkurjökull, a marine-terminating glacier in southeastern Iceland, using terrestrial radar interferometry. Journal of Glaciology.



(Photos: Dixon)

Ground Penetrating Radar

Use of ground-penetrating radar (GPR) for polar field-based applications has occurred since the 1950's. A handful of institutions have their own system, leading to a range of survey wavelengths, footprints, and vertical and horizontal resolutions. The result is a range of vertical accuracies and precisions.

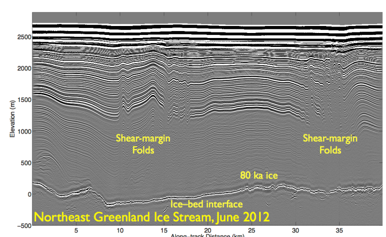
Applications:
Surface elevation; and ice thickness; subglacial lithology and hydrology properties; basal-melt rate; strain-rate; and temperature structure of the ice sheet.

Field:
GPR instruments are relatively small (< 200 lbs) and relatively quick to setup (2 h).

Data processing and access:
There are many data-processing and interpretation packages, but no standard data format for the data. NSF-funded researchers archive their data at the NSIDC.

Contact:
Knut Christianson, New York University (knut.christianson@gmail.com)

Christianson, Jacobel, Horgan, Anandakrishnan, & Alley (2012). Subglacial Lake Whillans—Ice-penetrating radar and GPS observations of a shallow active reservoir beneath a West Antarctic ice stream. Earth and Planetary Science Letters, 331, 237-245.



(Photos: Christianson)

Repeat/Time-Lapse Photography

Early applications of time-lapse photography, for glaciological applications, dates back to the 1970's. Today, power improvements and memory capacity have allowed for longer instrument deployments.

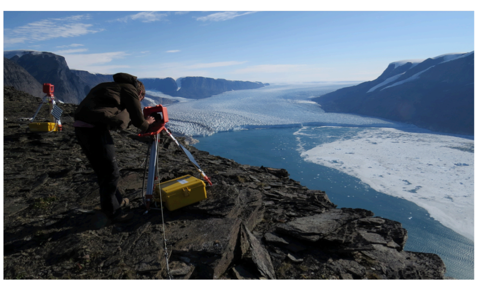
Applications:
Glacier velocities; glacier hydrology; ice/ocean interactions; and event detection.

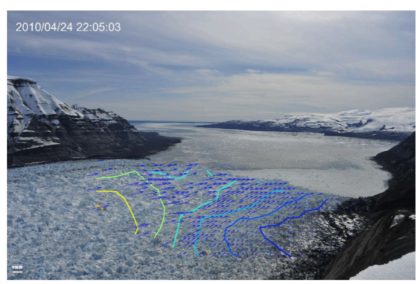
Field:
Setup takes a couple of hours; service thereafter is ~10 min, at least once per year.

Data processing and access:
Data volume is large. Currently, there isn't an established data archive. However, 160,000 images of Columbia Glacier, AK are now at ACADIS-NSIDC (http://nsidc.org/acadis/).

Contact:
Timothy Bartholomaus, University of Texas, Institute for Geophysics
(timb@ig.utexas.edu)

Bartholomaus, Larsen, & O'Neel (2013). Does calving matter? Evidence for significant submarine melt. Earth and Planetary Science Letters, 380, 21-30.





(Photos: Bartholomaus)

Spectral Induced Polarization (SIP)

Spectral induced polarization (SIP) measures complex electrical conductivity as a function of frequency. Ice content can be uniquely obtained by measuring the frequency dependence of the electrical properties over a large frequency range (20 kHz – 10 Hz). In addition, the electrical properties of permafrost are temperature-dependent, which can allow for an estimate of subsurface temperature.

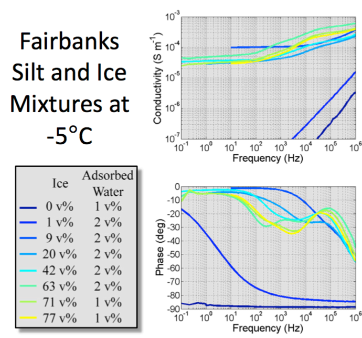
Applications:
Map subsurface ice content and ice chemistry or temperature.

Field:
Current technology is limited: 1) it's slow due to galvanic coupling; a two-man crew can collect 100 m of data in about a day. Another goal is to make a version of the sensor that couples capacitively (similar to OhmMapper but with multiple frequencies).

Data processing and access:
This is an emerging field. Data volume is low; processing is simple, as data collected can be inverted in the field. Data are not publically archived.

Contact:
David Stillman, Southwest Research Institute (dstillman@boulder.swri.edu)

Grimm & Stillman (in review). Field Test of Detection and Characterization of Subsurface Ice Using Broadband Spectral Induced Polarization. Permafrost and Periglacial Processes.



(Photos: Stillman)

Hot Water Drills:
University of Alaska, Fairbanks (UAF)

Use of hot water drills in the polar regions dates back to the 1970's and the early work of CRREL. The systems remain relatively unchanged, requiring a water source, a pump, heaters, hoses, and a drilling nozzle. These drills are commonly used to drill through ice shelves (AAD, BAS, and UAF) or to access the bottom of the ice sheets. The cost and logistics remain a limitation of this technology. The University of Alaska, Fairbanks, Hot Water Drill was used to access the water in the cavity of Pine Island Glacier.

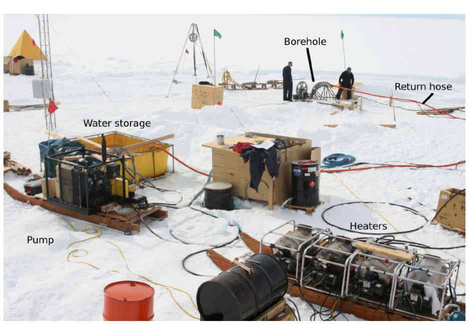
Applications:
Boreholes can be used for englacial, subglacial and sub-ice-shelf process studies. Other applications include subglacial lake access and the deployment of long-term observatories (e.g., IceCube neutrino observatory). At Pine Island Glacier, measurements included: ocean properties (temperature, salinity, flow); melt rates; ice temperatures; sediment core; and borehole camera.

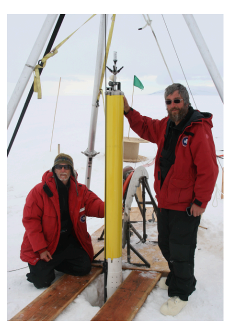
Field:
Drilling through an ice shelf requires a substantial drill. The UAF drill is considered a 'light-weight' drill, and is $O(10{,}000)$ lb, which generally necessitates deployment via fixed-wing. The drill is limited to 500–1500 m depth.

Data processing and access:
There are few standard instruments. Currently, there isn't an established data archive.

Contact:
Martin Truffer, University of Alaska, Fairbanks (truffer@gi.alaska.edu)

Stanton, Shaw, Truffer, Corr, Peters, Riverman, Bindschadler, Holland, & Anandakrishnan (2013). Channelized ice melting in the ocean boundary layer beneath Pine Island Glacier, Antarctica. Science, 341(6151), 1236-1239.





(Photos: Truffer)

Hot Water Drills:
University of Nebraska, Lincoln (UNL), Roving Hot Water Drill System (HWDS)

The University of Nebraska, Lincoln, Roving Hot Water Drill System (HWDS) was used to assess the interface between the Ross Ice Shelf and the water in the cavity below; it allowed for the deployment of Submersible Capable of under Ice Navigation and Imaging (SCINI); SCINI has a 15-cm diameter. This deployment was part of a larger Sub-Ice Marine and Planetary Analog Ecosystems (SIMPLE) study. A future submersible associated with this project, similar to SCINI, is called 'Icefin' and has a 25-cm diameter.

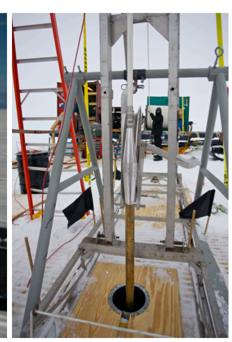
Applications:
SIMPLE, as with other ice-shelf drilling operations, is intended to study the ice–ocean interface, at the base of the ice shelves; this environment is being used as an analog to Europa and thus as a source of ground-truth observations for an ice-penetrating radar for the Europa Clipper mission.

Field:
Drilling through an ice shelf requires a substantial drill. The UNL drill is considered a 'mobile' drill, and traverses to the field on a sled platform. The drill is limited to 1000 m depth and creates a ~30-cm diameter hole.

Data processing and access:
Currently, there isn't an established data archive.

Contact:
Britney Schmidt, Georgia Institute of Technology (britney.schmidt@eas.gatech.edu)
UNL Drill: http://www.wissard.org/wissard-science/technology/hot-water-drill

Tulaczyk, Mikucki, Siegfried, Priscu, Barcheck, Beem, Behar, Burnett, Christner, Fisher, Fricker, Mankoff, Powell, Rack, Sampson, Scherer, & Schwartz (2014). WISSARD at Subglacial Lake Whillans, West Antarctica: scientific operations and initial observations. Annals of Glaciology, 55(65), 51-58.
Slawek Tulaczyk, University of California, Santa Cruz (tulaczyk@es.ucsc.edu)



(Photos: Schmidt)

Rapid Access Ice Drill (RAID)

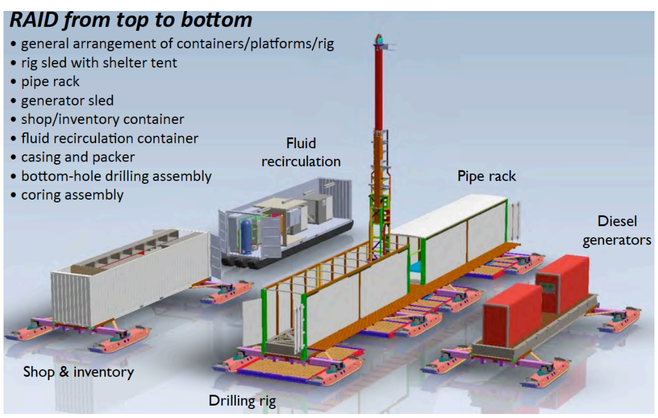
The Rapid Access Ice Drill (RAID) is intended to be a mobile platform for rapidly drilling to the ice–bedrock interface. It will collect both ice and rock cores. It will be deloyed to Antarctica in 2016-2017.

Applications:
This type of drilling supports numerous fields of research, including geology, glaciology, paleoclimate, landscape evolution, heat flow, microbiology, geodynamics, and astrophysics.

Field:
The goal is to achieve borehole access to 2500–3300 m depth, with a 8–10 cm diameter, in short timeframe (hours) and to sample the bed interface and retrieve ≥25 m of bedrock cores, with ≤5 cm diameter.

Data processing and access:
Currently, there isn't an established data archive.

Contact:
John Goodge, University of Minnesota (jgoodge@d.umn.edu)
US Ice Drilling Program Office: http://icedrill.org/
US IDPO RAID: http://icedrill.org/documents/view.shtml?id=612



(Photos: Goodge)

Other Ice Drills

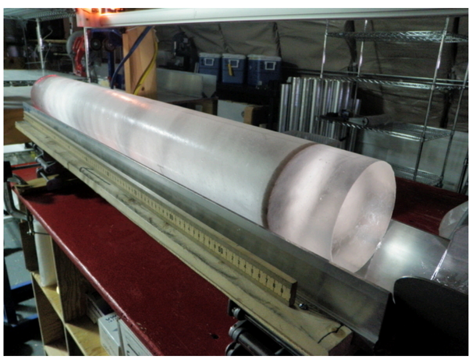
While some drills are institutional resources (e.g., UAF and UNL hot water drills), the NSF established the US Ice Drilling Program Office (IDPO) in 2008. The US Ice Drilling Program's mission is to conduct integrated planning for the ice drilling science and technology communities, and to provide drilling technology and operational support that will enable the community to advance the frontiers of science.

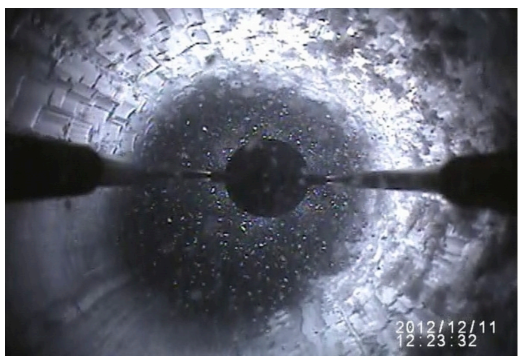
Applications:
The applications are numerous, as IDPO maintains non-coring and coring drills for both englacial and subglacial studies.

Field:
The IDPO houses 2 non-coring drills and 12 coring drills. Their inventory varies with respect to maximum depth, complexity of terrain (http://icedrill.org/equipment/).

Data processing and access:
There are few standard instruments. Currently, there isn't an established data archive.

Contact:
US Ice Drilling Program Office: http://icedrill.org/
US Ice Drilling Program Office Library: http://icedrill.org/library/





(Photos: IDPO)

2a) Airborne instrumentation

Airborne Topographic Mapper (ATM)

Airborne Topographic Mapper (ATM) is a 532-nm wavelength, variable repetition rate (3000 to 10,000 Hz), laser altimeter. ATM is a conically scanning (15° off-nadir) lidar; with a typical ground clearance of 750–1000 m, it creates a 350–500 m swath. It has a vertical RMS over snow and ice of ~10 cm.

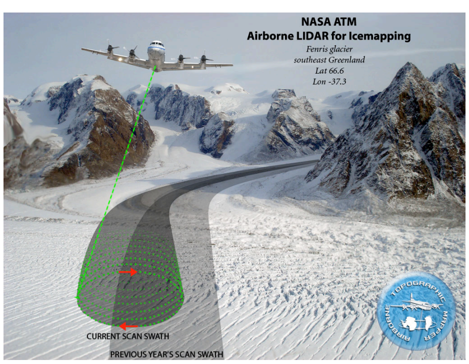
Applications:
Surface (e.g., ground, ice, or ocean) elevation; and ice-surface change.

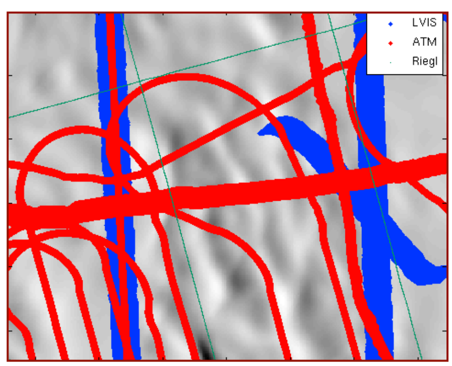
Platform:
-NASA Operation IceBridge (OIB): ATM is based out of Wallops, VA and has flown on the Twin Otter, P-3B, DC-8, and LC-130.

Data processing and access:
-OIB: surveyed Greenland and Antarctica (2009-2014). L0 through L2 elevation, slope and roughness datasets are available through the OIB portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
William Krabill, NASA Wallops (william.b.krabill@nasa.gov)

Krabill, Abdalati, Frederick, Manizade, Martin, Sonntag, Swift, Thomas, & Yungel (2002). Aircraft laser altimetry measurement of elevation changes of the Greenland ice sheet: Technique and accuracy assessment. Journal of Geodynamics, 34(3/4), 357–376.





(Photo: Krabill, Smith)

Land, Vegetation and Ice Sensor (LVIS)

Land, Vegetation and Ice Sensor (LVIS) is a 1064-nm wavelength laser altimeter. LVIS is a diagonally scanning (12° off-nadir) lidar; with a typical ground clearance of 10 km, it creates a 2 km swath. It has cm-level vertical precision.

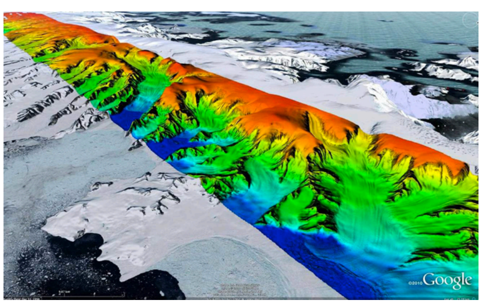
Applications:
Surface (e.g., ground, ice, or ocean) elevation; and ice-surface change.

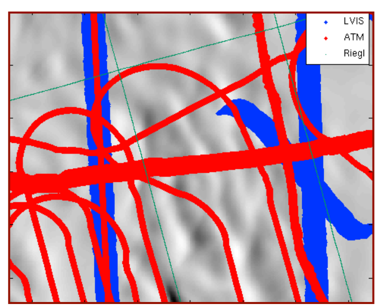
Platform:
-NASA Operation IceBridge (OIB): LVIS is based out of NASA Goddard and has flown on the P-3B, DC-8, King Air B-200, and HU-25C Falcon.

Data processing and access:
-OIB: surveyed Greenland (2009-2013) and Antarctica (2009-2011). L0 through L2 geo-located surface elevation datasets are available through the OIB portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
Bryan Blair, NASA Goddard (james.b.blair@nasa.gov)
Ben Smith, University of Washington, Applied Physics Laboratory
(bsmith@apl.washington.edu)

Blair, Rabine, & Hofton (1999). The Laser Vegetation Imaging Sensor: a medium-altitude, digitisation-only, airborne laser altimeter for mapping vegetation and topography. ISPRS Journal of Photogrammetry and Remote Sensing, 54(2), 115-122.





(Photo: NASA, Smith)

University of Alaska, Fairbanks (UAF), Geophysical Institute Airborne Scanning LiDAR

University of Alaska, Fairbanks (UAF), Geophysical Institute Airborne Scanning LiDAR is a commercial near-infrared laser altimeter, based on the Riegl LMS-Q240i. It is a scanning (30° off-nadir) lidar; with a typical ground clearance of 500 m, it creates a 500 m swath.

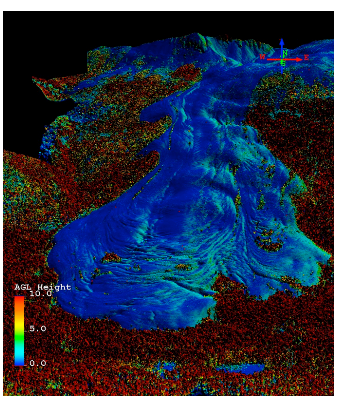
Applications:
Surface (e.g., ground, ice, or ocean) elevation; and ice-surface change.

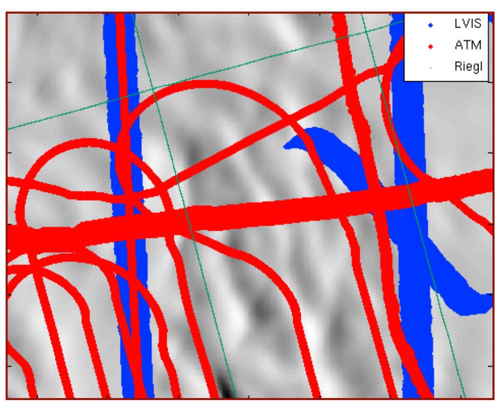
Platform:
-NASA Operation IceBridge (OIB)/AK: the Airborne Scanning LiDAR is based out of UAF and has flown on the DHC-3 Twin Otter and a Cessna 180.

Data processing and access:
-OIB/AK: surveyed Alaska (2009-2012). L1B geolocated surface elevation triplets and corrected position and attitude datasets are available through the OIB portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
Chris Larsen, University of Alaska, Fairbanks, Geophysical Institute
(Chris.Larsen@gi.alaska.edu)
Ben Smith, University of Washington, Applied Physics Laboratory
(bsmith@apl.washington.edu)

Johnson, Larsen, Murphy, Arendt, & Zirnheld (2013). Mass balance in the Glacier Bay area of Alaska, USA and British Columbia, Canada using airborne laser altimetry. Journal of Glaciology, 59(216), 632-648.





(Photo: Larsen, Smith)

University of Texas, Institute for Geophysics (UTIG), Profiler

University of Texas, Institute for Geophysics, Profiler is a multibeam, scanning photon counting laser altimeter. With a typical ground clearance of 800 m, it creates a 400 m swath with decimeter precision vertical precision.

Applications:
Surface (e.g., ground, ice, or ocean) elevation; and ice-surface change.

Platform:
-University of Texas, Institute for Geophysics (UTIG): the UTIG Profiler has flown on the DHC-3 Twin Otter and the Basler BT-67.

Data processing and access:
-UTIG: surveyed the Totten Glacier region (2010–2012). L1B geolocated elevations and L4 slope and elevation datasets are available through the Operation IceBridge portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
Duncan Young, University of Texas, Institute for Geophysics (duncan@ig.utexas.edu)
Benjamin Smith, University of Washington, Applied Physics Laboratory (bsmith@apl.washington.edu)

http://www.ig.utexas.edu/research/facilities/aero/
http://www.nasa.gov/mission_pages/icebridge/instruments/utig-lidar.html

Center for Remote Sensing of Ice Sheets (CReSIS),
Multichannel Coherent Radar Depth Sounder (MCoRDS)

The Center for Remote Sensing of Ice Sheets (CReSIS) Multichannel Coherent Radar Depth Sounder (MCoRDS/I) is currently a 195-MHz, 30-MHz bandwidth radar sounder, intended to measure ice thickness, internal layering, and bed properties. It can penetrate ice up to ~4 km thick.

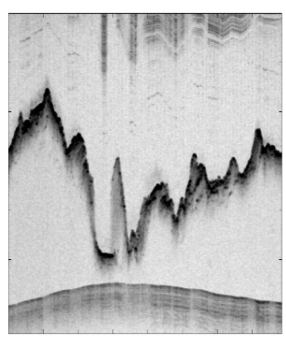
Applications:
Ice thickness; internal layering; and bed properties.

Platform:
-CReSIS MCoRDS has flown on the Twin Otter, P-3B, and DC-8. The antenna configuration is a dipole array mounted on the wings and fuselage.

Data processing and access:
-CReSIS MCoRDS surveyed Greenland (1993, 1995-1999, 2001-2014) and Antarctica (2002, 2004-2005, 2009-2013). L1B through L2 ice thickness datasets are available through the Operation IceBridge portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
Carlton Leuschen, (leuschen@ku.edu) and Prasad Gogineni (gogineni@eecs.ku.edu)
University Kansas, Center for Remote Sensing of Ice Sheets (CReSIS)

Li, Paden, Leuschen, Rodriguez-Morales, Hale, Arnold, Crowe, Gomez-Garcia, & Gogineni (2013). High-altitude radar measurements of ice thickness over the Antarctic and Greenland ice sheets as a part of Operation IceBridge. Geoscience and Remote Sensing, IEEE Transactions on, 51(2), 742-754.



(Photo: Leuschen)

Center for Remote Sensing of Ice Sheets (CReSIS), UWB Radar

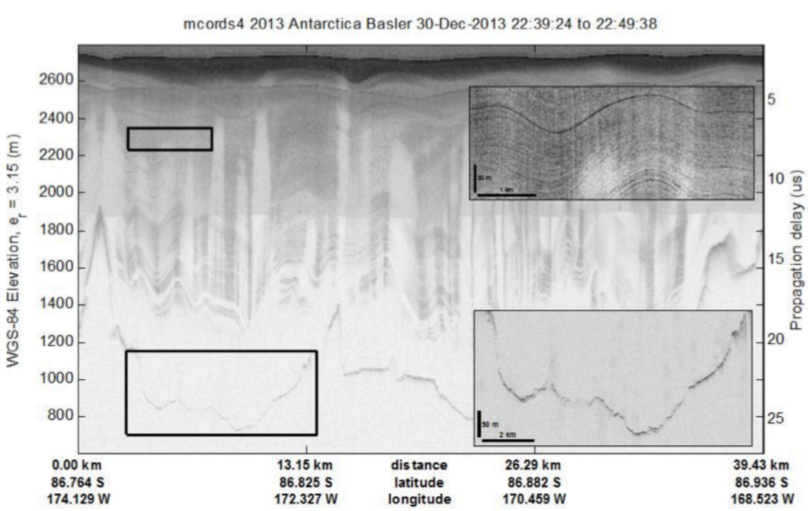
The Center for Remote Sensing of Ice Sheets (CReSIS) UWB Radar is new sensor, at 160 - 600 MHz frequency and 0.5–2 m wavelength in ice, intended to determine ice thickness, internal layering, and bed properties. It can penetrate the ice surface up to about 3 km.

Applications:
Ice thickness; internal layering; and bed properties.

Platform:
-CReSIS UWB Radar is intended for installation on the Basler. The antenna configuration is mounted on the wings and fuselage.

Data processing and access:
-CReSIS UWB is scheduled to be deployed to Greenland in 2015. Data are expected to be available through the Operation IceBridge portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
Carlton Leuschen, (leuschen@ku.edu) and Prasad Gogineni (gogineni@eecs.ku.edu)
University Kansas, Center for Remote Sensing of Ice Sheets (CReSIS)



(Photo: Leuschen)

Center for Remote Sensing of Ice Sheets (CReSIS), Accumulation Radar

The Center for Remote Sensing of Ice Sheets (CReSIS) Accumulation Radar is a 750 MHz frequency and 40-cm wavelength sensor, intended to determine internal layering and bed properties. It can penetrate the ice surface up to about 500 m.

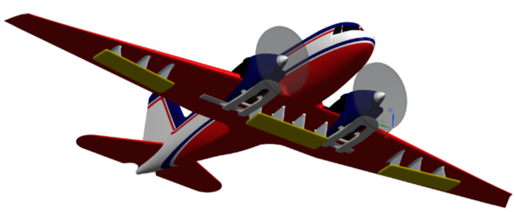
Applications:
Internal layering; and bed properties.

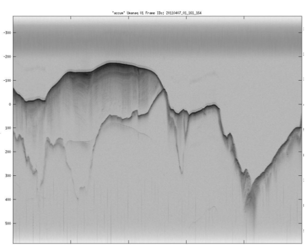
Platform:
-CReSIS Accumulation Radar has flown on the Twin Otter and P-3B. The antenna configurations are either a patch array or a Vivaldi array. Nominal altitude is 20,000 ft.

Data processing and access:
-CReSIS Accumulation Radar surveyed Greenland (2010-2014) and Antarctica (2009, 2011). L1B geolocated radar echo strength profiles datasets are available through the Operation IceBridge portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
Carlton Leuschen, (leuschen@ku.edu) and Prasad Gogineni (gogineni@eecs.ku.edu)
University Kansas, Center for Remote Sensing of Ice Sheets (CReSIS)

Lewis, Patel, Owen, Rodriguez-Morales, Leuschen, Seguin, Ledford, Player, & Gogineni (2009). A radar suite for ice sheet accumulation measurements and near-surface internal layer mapping. In Geoscience and Remote Sensing Symposium, 2009 IEEE International, IGARSS 2009 (Vol. 5, pp. V-441).





(Photo: Leuschen)

Center for Remote Sensing of Ice Sheets (CReSIS), Snow Radar

The Center for Remote Sensing of Ice Sheets (CReSIS) Snow Radar is a 5-GHz frequency and 7.5-cm wavelength sensor, intended to determine snow cover, topography, and layering. It can penetrate the ice surface up to about 80 m.

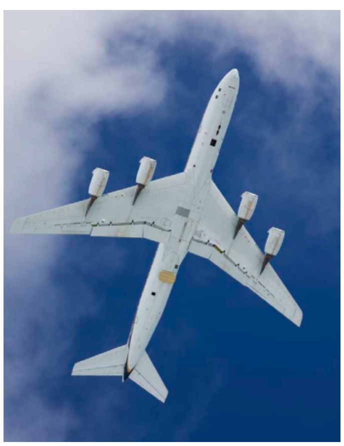
Applications:
Snow cover; topography; and layering.

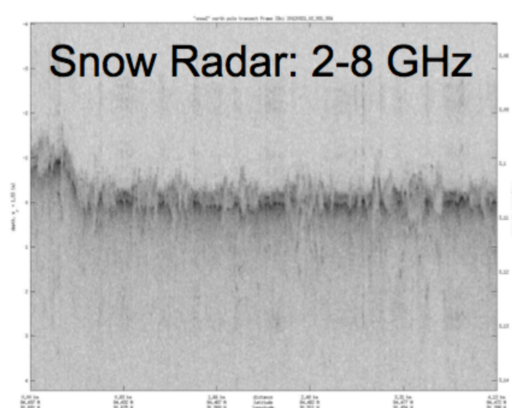
Platform:
-CReSIS Snow Radar has flown on the P-3B, DC-8, and Basler. The antenna configuration is a horn. Nominal altitude is 30,000 ft.

Data processing and access:
-CReSIS Snow Radar surveyed Greenland (2009-2014) and Antarctica (2009, 2011-2013). L1B geolocated radar echo strength profiles datasets are available through the Operation IceBridge portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
Carlton Leuschen, (leuschen@ku.edu) and Prasad Gogineni (gogineni@eecs.ku.edu)
University Kansas, Center for Remote Sensing of Ice Sheets (CReSIS)

Gogineni, Yan, Gomez, Rodriguez-Morales, Paden, & Leuschen (2013,). Ultra-wideband radars for remote sensing of snow and ice. In Microwave and RF Conference, 2013 IEEE MTT-S International (pp. 1-4).





(Photo: Leuschen)

Center for Remote Sensing of Ice Sheets (CReSIS), Ku-Band Radar

The Center for Remote Sensing of Ice Sheets (CReSIS) Ku-Band Radar is a 15-GHz frequency and 2-cm wavelength sensor, intended to determine topography and layering. It can penetrate the ice surface up to about 15 m.

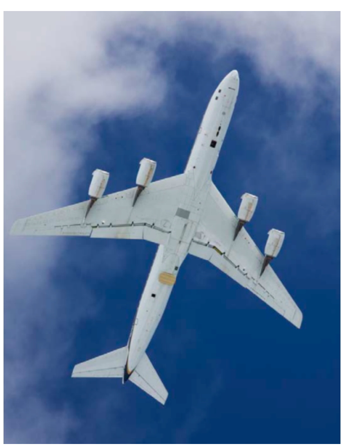
Applications:
Topography; and layering.

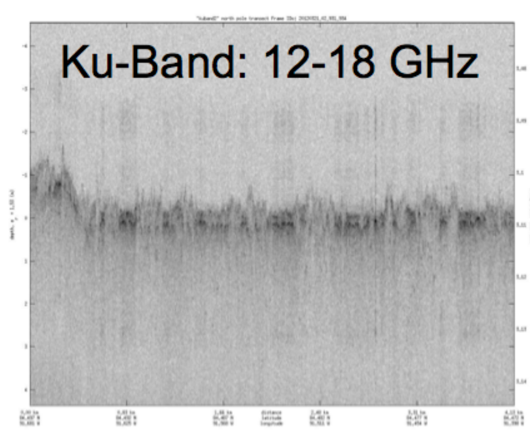
Platform:
-CReSIS Ku-Band Radar has flown on the Twin Otter, P-3B, DC-8, and Basler. The antenna configuration is a horn. Nominal altitude is 30,000 ft.

Data processing and access:
-CReSIS Ku-Band Radar surveyed Greenland (2009-2014) and Antarctica (2009, 2011-2013). L1B geolocated radar echo strength profiles datasets are available through the Operation IceBridge portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
Carlton Leuschen, (leuschen@ku.edu) and Prasad Gogineni (gogineni@eecs.ku.edu)
University Kansas, Center for Remote Sensing of Ice Sheets (CReSIS)

Gogineni, Yan, Gomez, Rodriguez-Morales, Paden, & Leuschen (2013,). Ultra-wideband radars for remote sensing of snow and ice. In Microwave and RF Conference, 2013 IEEE MTT-S International (pp. 1-4).





(Photo: Leuschen)

University of Texas, Institute for Geophysics (UTIG),
High Capability Radar Sounder (HiCARS)

University of Texas, Institute for Geophysics (UTIG), High Capability Radar Sounder (HiCARS), is a VHF ice-penetrating radar, which operates in frequency-chirped mode from 52.5–67.5 MHz. HiCARS allows for phase coherent recording of radar returns for advanced processing. It has been operated extensively in Antarctica and Greenland and has regularly sounded deep and highly crevassed ice, penetrating the ice surface in excess of about 4 km.

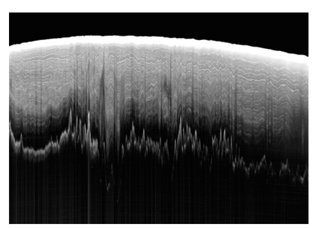
Applications:
Ice thickness; internal layering; and bed properties.

Platform:
-UTIG HiCARS has flown on the Twin Otter and Basler. The antenna configuration is a twin dipole array mounted on the wings.

Data processing and access:
-UTIG HiCARS Radar surveyed Antarctica (2009–2012). L0 through L2 geolocated ice thickness datasets are available through the Operation IceBridge portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
Dustin Schroeder, Jet Propulsion Laboratory, California Institute of Technology (dustin.m.schroeder@jpl.nasa.gov)
Duncan Young, University of Texas, Institute for Geophysics (duncan@ig.utexas.edu)

Young, Wright, Roberts, Warner, Young, Greenbaum, Schroeder, Holt, Sugden, Blankenship, van Ommen, & Siegert (2011). A dynamic early East Antarctic Ice Sheet suggested by ice-covered fjord landscapes. Nature, 474(7349), 72-75.


(Photo: UTIG)

Aerogravity

Polar applications of gravimetry enable determination of aspects of the subglacial bed, not easily determined by other instrumentation.

Applications:
Bathymetry under ice shelves and sea ice, bed geology, and sea ice freeboard.

Platform:
-NASA Operation IceBridge (OIB): currently, the OIB gravimeter is a Sander Geophysics Limited AIRGrav, which has flown on the Twin Otter, P-3B, and the DC-8.

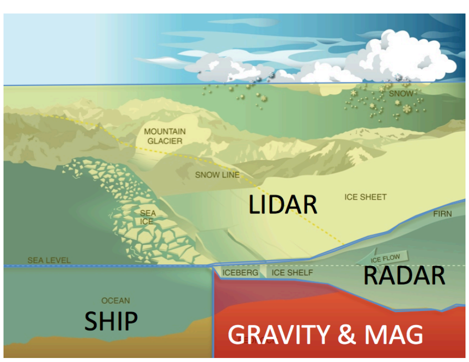
-University of Texas, Institute for Geophysics (UTIG): currently, UTIG uses a GT-1A Gravimeter, integrated with a ski-equipped DC-3T.

Data processing and access:
-OIB: surveyed Greenland (2010-2012) and Antarctica (2010-2014). L1B geolocated anomalies and L3/L4 bathymetry profiles are available through the Operation IceBridge portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

-UTIG: surveyed the Totten Glacier region (2012). L0 through L2 geolocated anomalies are available through the Operation IceBridge portal at NSIDC (http://nsidc.org/data).

Contact:
Kirsteen Tinto, Columbia University, Lamont-Doherty Earth Observatory (tinto@ldeo.columbia.edu)
Jamin Greenbaum, University of Texas, Institute for Geophysics (jamin@utexas.edu)

Tinto & Bell (2011). Progressive unpinning of Thwaites Glacier from newly identified offshore ridge: Constraints from aerogravity. Geophysical Research Letters, 38(20).



(Photos: Tinto & Greenbaum)

Aeromagnetic

Polar applications of magnetometry enable us to determine aspects of the subglacial bed not easily determined through other instrumentation.

Applications:
Subglacial geology.

Platform:
-NASA Operation IceBridge (OIB): currently, the OIB main magnetometer is Scintrex CS3 Cesium vapor magnetometer, owned and operated by Lamont-Doherty Earth Observatory; it has flown on the Twin Otter, and the P-3.

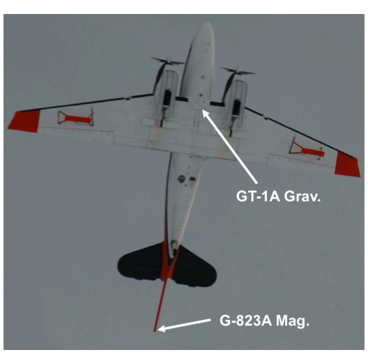
-University of Texas, Institute for Geophysics (UTIG): currently, UTIG uses a G823A magnetometer, integrated with a ski-equipped DC-3T.

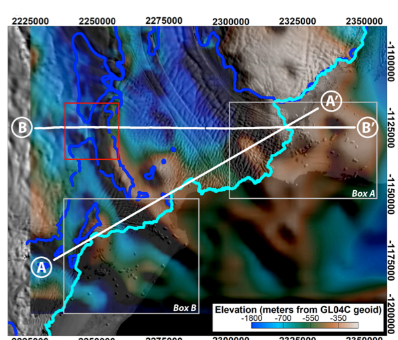
Data processing and access:
-OIB: surveyed Greenland (2011-2012) and Antarctica (2013). L0 through L1B geolocated anomalies are available through the Operation IceBridge portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

-UTIG: surveyed the Totten Glacier region (2012). L0 through L2 geolocated anomalies are available at the NSIDC (http://nsidc.org/data).

Contact:
Kirsteen Tinto, Columbia University, Lamont-Doherty Earth Observatory (tinto@ldeo.columbia.edu)
Jamin Greenbaum, University of Texas, Institute for Geophysics (jamin@utexas.edu)

Greenbaum et al. (in review). Increasing Ocean Access to Totten Glacier, East Antarctica, Nature Geoscience.





(Photos: Tinto & Greenbaum)

Airborne Synthetic Aperture Radar (SAR)

Airborne Synthetic Aperture Radars (SAR) have included:

-GLISTIN-A: Ka-Band (8.6 mm), single pass interferometer developed explicitly for land-ice topographic mapping;

-UAVSAR: L-Band, capable of repeat-pass interferometry for velocity mapping of ice-sheets of glacial regions;

-SnowSAR: Ku-band polarimetric SAR, primarily used as calibration and validation tool for CoreH2O; and

-GeoSAR: P/X Band interferometer, partial polarimeter, commercial system used over sea ice.

Applications:
Ice velocity, sea ice freeboard, dynamics, and volume changes of mountain glaciers.

Platform:
-GLISTIN-A: has flown on the NASA G-III, in a pod.

Data processing and access:
-GLISTIN-A: has surveyed Alaska, Greenland, and Antarctica. It is being transitioned from a PI-led instrument to a facility (JPL) sensor (2015). Data will be accessible in the future from ASF (https://www.asf.alaska.edu/).

Contact:
Delwyn Moller, JPL (delwyn.k.moller@jpl.nasa.gov)

Moller, Heavey, Rignot, Sadowy, Simard, & Zawadzki (2008). A Novel Ka-band Digitally Beamformed Interferometric Synthetic Aperture Radar for Glacier and Ice-sheet Topographic Mapping: Concept and Technology. In Synthetic Aperture Radar (EUSAR), 2008 7th European Conference on (pp. 1-4).

(Photos: Moller)

2b) Airborne platforms

Lamont-Doherty Earth Observatory, IcePod

Lamont-Doherty Earth Observatory's IcePod is an integrated ice sensing system operated on the NSF supported New York Air National Guard LC-130 aircraft during ongoing missions to Antarctica and Greenland. IcePod is a shared community resource. IcePod is intended to conduct long-range programs in the interior without installing large camps at elevation. IcePod is not dependent on single airframe. And finally, IcePod has the ability to collect science data during mission-related flights.

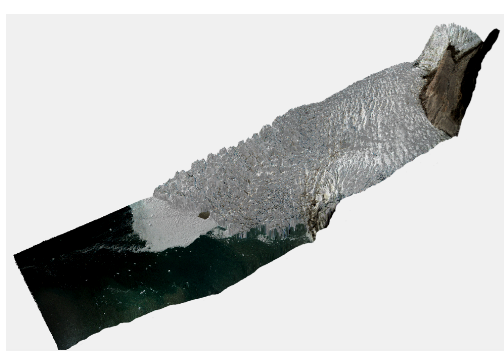
Applications:
Applications are numerous, including: outlet glacier dynamics; subglacial hydrology; grounding line stability; and extended time series analysis.

Sensors:
Riegl VQ580 Scanning Lidar; Imprx Color Camera; Sofradir IR Camera; Pyrometer; Deep Ice Radar; Shallow Ice Radar; GPS Novatel Span; and Litton LN200 IMU. Future sensors include: magnetometer; gravity meter; and AXCTD.

Aircraft:
LC-130.

Data processing and access:
Data to be archived and served at Lamont-Doherty Earth Observatory (http://www.ldeo.columbia.edu/research/databases-repositories). Georeferenced files and associated meta-data will be available; raw data available on request.

Contact:
Robin Bell, Lamont-Doherty Earth Observatory (robinb@ldeo.columbia.edu)
Nick Frearson, Lamont-Doherty Earth Observatory (nfre@ldeo.columbia.edu)
http://www.ldeo.columbia.edu/polar-geophysics-group/



(Photos: Frearson & Bell)

NASA Operation IceBridge (OIB)

NASA's Operation IceBridge (OIB) is the largest polar airborne survey ever flown. It was conceived as an airborne mission intended to bridge the data gap between ICESat and ICESat-2, however, OIB has its own unique science mission and requirements.

Applications:
Applications are numerous, including: ice-surface topography; bedrock topography beneath the ice sheets; grounding line position; ice and snow thickness; and sea ice distribution and freeboard.

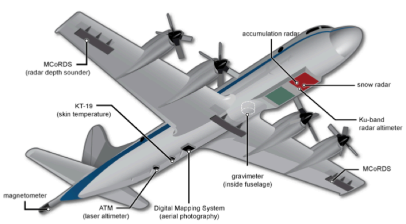
Sensors:
-NASA: Accumulation Radar; Airborne Meteorological Instruments; Airborne Topographic Mapper (ATM); Atmospheric Chemistry; Continuous Airborne Mapping By Optical Translator (CAMBOT); Digital Mapping System Camera (DMS); KT19 Infrared Radiation Pyrometer; Ku-Band Radar Altimeter; Land, Vegetation, and Ice Sensor (LVIS); Magnetometer; Multichannel Coherent Radar Depth Sounder (MCoRDS); Navigation, State Parameter, and Microphysics LRT; Pathfinder Advanced Radar Ice Sounder (PARIS); Position/Avionics (POS/AV); Sander/LDEO Airborne Gravimeter (AIRGrav); Snow Radar; UAF Lidar; and WISE Radar Sounder.

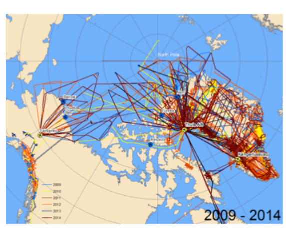
Aircraft:
P-3B Orion, DC-8, LC-130, C-130, King Air B-200, HU-25C Falcon, Gulfstream G-V, Basler BT-67, DeHavilland DHC-3 Twin Otter, and a Cessna 180.

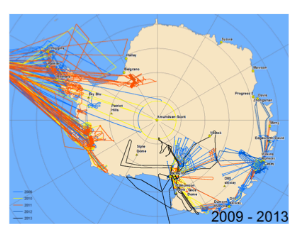
Data processing and access:
OIB mission observations and measurements, between 2009 and 2014, include coastal Greenland, coastal Antarctica, the Antarctic Peninsula, interior Antarctica, the southeast Alaskan glaciers, and Antarctic and Arctic sea ice. Data are available through the OIB portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
Lora Koenig, University of Colorado, Boulder, CIRES, NSIDC
http://nsidc.org/data/icebridge/

Koenig, Martin, Studinger, & Sonntag (2010). Polar airborne observations fill gap in satellite data. EOS Trans. AGU, 91(38), 333-334.







(Photos: Koenig)

NASA Arctic Radiation IceBridge Sea & Ice Experiment (ARISE)

NASA Arctic Radiation IceBridge Sea & Ice Experiment (ARISE) mission is to acquire well-calibrated data sets using aircraft and surface-based sensors. Specifically, ARISE will measure spectral and broadband radiative flux profiles, quantify surface characteristics, cloud properties, and other atmospheric state parameters under a variety of Arctic atmospheric and surface conditions, and coinciding with satellite overpasses when possible.

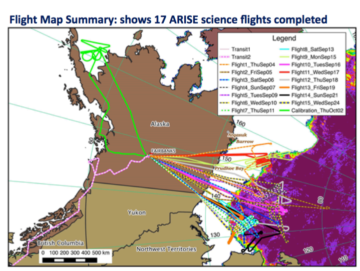
Applications:
To acquire detailed measurements of land and sea ice characteristics to help bridge a gap in NASA satellite observations of changing Arctic Ice conditions.

Sensors:
Solar Spectral Flux Radiometer (SSFR); Spectrometer for Sky-Scanning, Sun-Tracking Atmospheric Research (4STAR); Land, Vegetation, and Ice Sensor (LVIS); Broadband Infrared Radiometers (BBR); and Langley Aerosol Research Group Experiment (LARGE).

Aircraft:
C-130.

Data processing and access:
ARISE measurements started in August 2014, include Alaska and the Arctic Ocean.

Contact:
Bill Smith, NASA Langley Research Center (william.l.smith@nasa.gov)
https://espo.nasa.gov/missions/arise



(Photos: Hansen)

University of Texas, Institute for Geophysics (UTIG)

UTIG has a long history of aerogeophysical surveys in the polar regions:
1991-1997: CASERTZ- Corridor Aerogeophysics of the South East Ross Transect Zone
1997-2001: SOAR- Support Office for Aerogeophysical Research
2004-2005 AGASEA- Amundsen Sea Embayment
2009-Present: ICECAP

Applications:
Applications are numerous, including: ice surface topography; bedrock topography beneath the ice sheets; grounding line position; and ice and snow thickness.

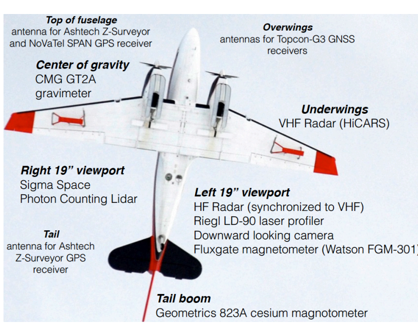
Sensors:
-ICECAP: GPS and Inertial Measurement Unit (Ashtech Z-Surveyor receiver, Topcon-G3 GNSS receiver, NovAtel SPAN GPS receiver); CMG GT2A Gravimeter; VHF High Capability Radar Sounder (HiCARS); HF Radar; Riegl LD-90 laser profiler; Sigma Space Photon-Counting Lidar; Watson FGM-301 Fluxgate Magnetometer; Geometrics 823A Cesium Magnotometer; Pressure Altimeter; and a Downward Looking Camera.

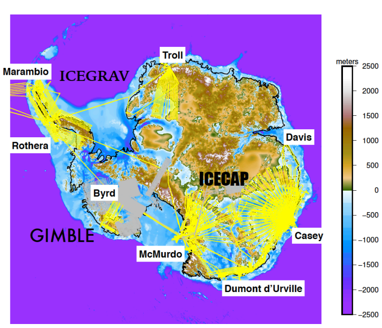
Aircraft:
DeHavilland DHC-3 Twin Otter (prior to 2005) and the Basler BT-67 (current).

Data processing and access:
ICECAP measurements, between 2009 and 2014, have generally been on the East Antarctic Ice Sheet, but have also included some measurements in Greenland. Data are available through the Operation IceBridge portal at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icebridge/).

Contact:
Duncan Young, University of Texas, Institute for Geophysics (duncan@ig.utexas.edu)
http://www.ig.utexas.edu/research/projects/icecap/

Young, Wright, Roberts, Warner, Young, Greenbaum, Schroeder, Holt, Sugden, Blankenship, van Ommen, & Siegert (2011). A dynamic early East Antarctic Ice Sheet suggested by ice-covered fjord landscapes. Nature, 474(7349), 72-75.





(Photos: Young)

Center for Remote Sensing of Ice Sheets (CReSIS), Unmanned Aircraft Systems (UAS)

The Center for Remote Sensing of Ice Sheets (CReSIS), Unmanned Aircraft Systems (UAS) program has instrumented platforms for radar remote sensing of ice sheets and sea ice, with a variety of payload verses performance options. Sensor development and miniaturization has increased vehicle autonomy and reliability. Many commercial UAS available; use requires flight approvals, air space user coordination, positive tracking and separation, and frequency management. Therefore, other interested researchers will require collaboration with the CReSIS platform development team. The CReSIS UAS program has a three-tiered approach to development:

> Tier A: for small, short-range (<1,000 km) aircraft capable of carrying a single science payload, operated locally from a field camp, affordable, and readily fleeted (~50 kg);
>
> Tier B: for medium range (~5,000 km) aircraft capable of carrying multiple science payloads, operated remotely from a base camp, affordable to only the largest of research teams, and not readily fleeted (~100 kg); and
>
> Tier C: for long Range (>10,000 km) vehicle capable of carrying ~150 kg payload, operated from off continent, affordable only to federal governments, and not readily fleeted.

Sensors and Applications:
Sensor options and applications are numerous, but limited by UAS payload Applications toward polar sciences are numerous.

Data processing and access:
CReSIS has conducted over 200 UAS flight tests in Antarctica, Greenland, and the USA. CReSIS specifically tested G1X UAS with HF/VHF sounder, which imaged the ice bed at SLW field camp, Antarctica, in 2014.

Contact:
Rick Hale, University Kansas, Center for Remote Sensing of Ice Sheets (CReSIS)
(rhale@ku.edu)
https://www.cresis.ku.edu/content/research/uas

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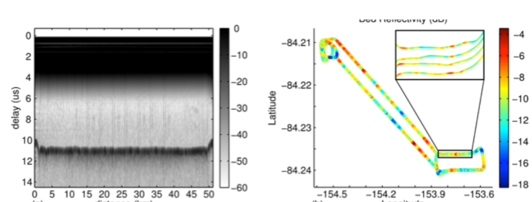


(Photos: Hale)

3) Satellite-borne instrumentation

NASA Ice, Cloud, and land Elevation Satellite-2 (ICESat-2)

The instrument onboard NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2), scheduled to launch in 2017, is a micro-pulse, multi-beam, photon-counting laser altimeter. The ICESat-2 sampling approach provides dense cross-track sampling to help scientists determine a surface's slope with each pass of the satellite.

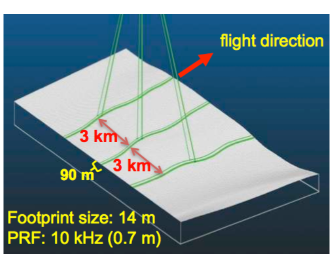
Applications:
ICESat-2 will make precise, repeated measurements of the surface of the Earth to assess the magnitude and causes of ice sheet changes. Other mission goals include producing monthly maps of sea ice freeboard and the determination of global vegetation height.

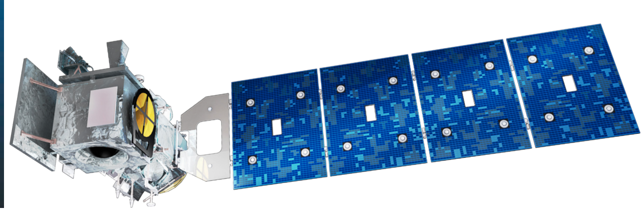
Sensors:
The sole instrument on ICESat-2 will be the Advanced Topographic Laser Altimeter System (ATLAS), which will emit visible, green laser pulses at a wavelength of 532 nm. A single laser beam will be split into 6 beams, arranged in 3 pairs, with 3.3 km between pairs and 90 m within each pair. ATLAS will have a high pulse-repetition rate of 10 kHz. This allows the satellite to take measurements every 70 cm along the track. Measurements will extend to 88° latitude.

Data processing and access:
ICESat-2 data will be in HDF-5 format and available at the National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/).

Contact:
Thorsten Markus, NASA (thorsten.markus-1@nasa.gov)
Thomas Neumann, NASA (thomas.neumann@nasa.gov)
http://icesat.gsfc.nasa.gov/icesat2

Abdalati, Zwally, Bindschadler, Csatho, Farrell, Fricker, Harding, Kwok, Lefsky, Markus, Marshak, Neumann, Palm, Schutz, Smith, Spinhirne, & Webb (2010). The ICESat-2 laser altimetry mission. Proceedings of the IEEE, 98(5), 735-751.





(Photos: NASA)

Active NASA Earth Observing System Satellites

NASA's Earth Observing System (EOS) is a coordinated series of polar-orbiting and low inclination satellites for long-term global observations. Five of these satellites closely follow one another in a group referred to as the Afternoon Constellation, or the A-Train. A-Train allows for near-simultaneous observations of a wide variety of parameters. NASA satellite data are available at a series of application-specific Distributed Active Archive Centers (DAACs; https://earthdata.nasa.gov/).

Active Satellites and Applications:

Aquarius (2011-Present): radiometer to assess sea-surface salinity (Argentina);

OSTM/Jason-2 (2008-Present): radar altimeter to assess sea surface height (France);

QuikSCAT (1999-Present): scatterometer to assess surface wind speed;

TRMM (1997-Present): various instruments to assess tropical rainfall (Japan);

EO-1 (2000-Present): various instruments for Earth imaging;

Landsat-7 (1999-Present): various bands for Earth imaging;

Landsat-8 (2013-Present): various bands for Earth imaging;

ACRIMSAT (1999-Present): various instruments to assess total solar irradiance (TSI);

SORCE (2003-Present): various instruments to assess incoming X-ray, UV, visible, near-infrared, and total solar radiation;

GRACE (2002-Present): 2 satellites to assess Earth's gravity field (Germany);

Suomi NPP (2011-Present): various instruments to assess clouds, oceans, vegetation, ice, and atmosphere for weather applications;

GPM (2014-Present): a precipitation radar and a microwave imager to assess precipitation (Japan);

Terra (1999-Present): various instruments to assess the state of Earth's environment and ongoing changes in its climate system (Japan, Canada);

Aqua (2002-Present): part of the A-Train constellation; various instruments to assess precipitation, evaporation, and cycling of water (Japan, Brazil);

CALIPSO (2006-Present): part of the A-Train constellation; various instruments to assess aerosols and clouds (France);

CloudSat (2006-Present): part of the A-Train constellation; profiling radar to assess clouds (Canada);

Aura (2004-Present): part of the A-Train constellation; various instruments to assess Earth's ozone layer, air quality and climate (Netherlands, Finland, UK); and

OCO-2 (2014-Present): part of the A-Train constellation; 3 spectrometers to assess atmosphere carbon dioxide.

European Space Agency Cryosat-2

ESA's Cryosat-2, operational since 2010, carries a radar altimeter that operates in 3 distinct modes: Synthetic Aperture Radar (SAR) mode, over sea ice; SAR Interferometric (SARIn) mode, over steeply-sloping ice-sheet margins; and Low Resolution Mode (LRM), over areas of the continental ice sheets, over oceans and over land not covered by other modes.

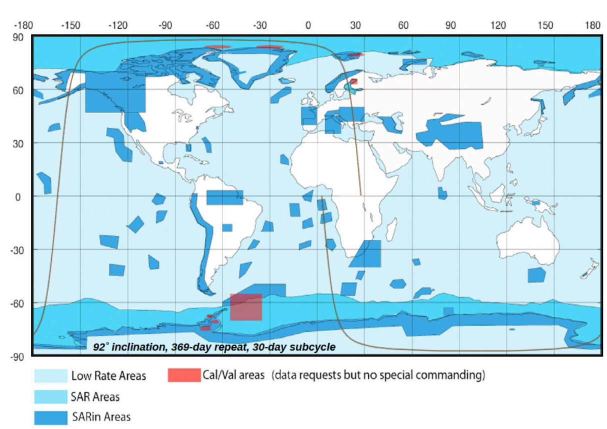
Applications:
Cryosat-2 precisely monitors the changes in the thickness of marine ice floating in the polar oceans and variations in the thickness of the vast ice sheets that overlie Greenland and Antarctica.

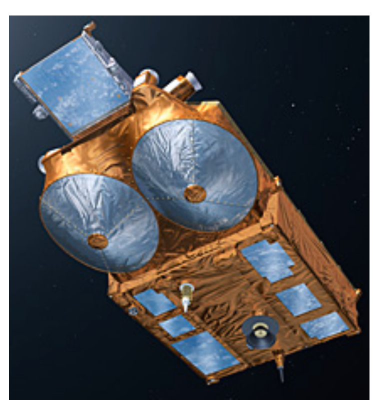
Sensors:
The sole instrument on Cryosat-2 is SIRAL-2, a radar altimeter that will send a burst of pulses with an interval of 50 µs. Each strip of data is about 250 m wide and the interval between bursts is arranged so that the satellite moves forward by 250 m each time. Vertical precision ~11 cm over flat surfaces, absolute accuracy heavily dependent on surface topography. Measurements will extend to 88° latitude.

Data processing and access:
Cryosat-2 data is available to registered users on the ESA website (https://earth.esa.int/web/guest/home).

Contact:
Nathan Kurtz, NASA (nathan.t.kurtz@nasa.gov)

Wingham, Francis, Baker, Bouzinac, Brockley, Cullen, de Chateau-Thierry, Laxon, Mallow, Mavrocordatos, Phalippou, Ratier, Rey, Rostan, Viau, & Wallis (2006). CryoSat: A mission to determine the fluctuations in Earth's land and marine ice fields. Advances in Space Research, 37(4), 841-871.




(Photos: Kurtz)

Synthetic Aperture Radar (SAR) and Interferometric SAR (InSAR)

SAR satellites have been used in polar research to, among other things, characterize ice motion.

Applications:
Surface roughness or wetness; topography; and surface deformation (motion).

Sensors:

X-Band (3.1 cm and 9.6 GHz): TerraSAR-X (2007-Present); Tandem-X (2010-Present); and Cosmo-Skymed (1-4) (2007-Present);

C-Band (5 cm and 6 GHz): ERS-1 (1991-2000); ERS-2 (1995-2003); Envisat (2002-2012); RADARSAT-1 (1995-2013); RADARSAT-2 (2007-Present); Sentinel-1A (2014-Present); and Sentinel-1B (~2016);

S-Band (12 cm and 3 GHz): NISAR (~2019); and

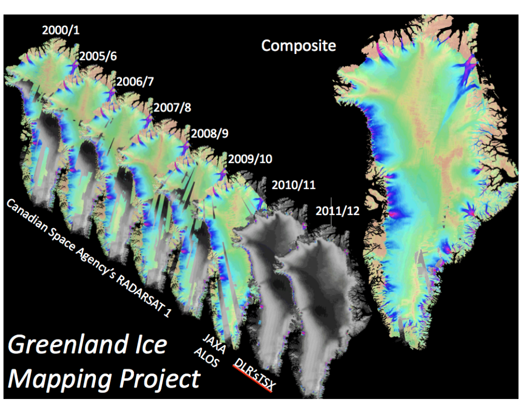
L-Band (23 cm and 1.25 GHz): Seasat (1978); JERS-1 (1992-1998); ALOS (2006-2011); ALOS-2 (2014-Present); and NISAR (~2019).

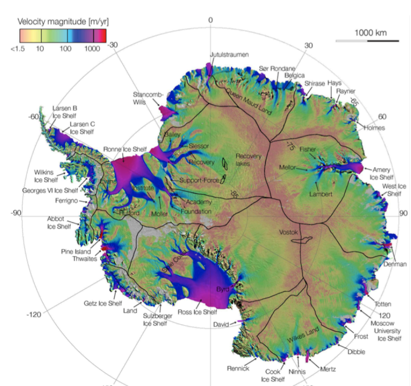
Data processing and access:
SAR and InSAR datasets are available for purchase or via proposal at the Alaska SAR facility: (https://www.asf.alaska.edu/).

Contact:
Mark Fahnestock, University of Alaska, Fairbanks (fahnestock@gi.alaska.edu)

Rignot, Mouginot, & Scheuchl (2011). Ice flow of the Antarctic ice sheet. Science, 333(6048), 1427-1430.

Fahnestock, Bindschadler, Kwok, & Jezek (1993). Greenland ice sheet surface properties and ice dynamics from ERS-1 SAR imagery. Science, 262(5139), 1530-1534.





(Photos: Fahnestock)

Commercial Satellite Imagery

The Polar Geospatial Center (http://www.pgc.umn.edu/), funded primarily through the NSF, has a unique relationship with the National Geospatial-Intelligence Agency (NGA) to obtain sub-meter imagery and make it available to NSF researchers, strictly governed by licensing agreements between NGA and the commercial imagery provider (DigitalGlobe).

Applications:
High-resolution mapping; stereo imagery allows for the generation of Digital Elevation Models (DEMs); velocity maps; and change detection.

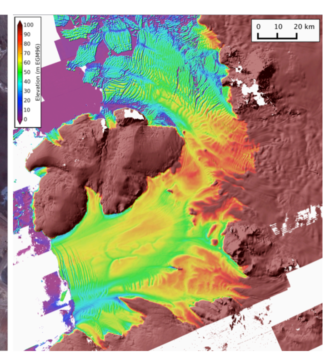
Sensors:

- IKONOS (1999-Present): 100 cm panchromatic and 400 cm multispectral;
- QuickBird (2001-Present): 60 cm panchromatic and 240 cm multispectral;
- WorldView-1 (2007-Present): 42 cm panchromatic;
- GeoEye-1 (2008-Present): 41 cm panchromatic and 165 cm multispectral;
- WorldView-2 (2009-Present): 46 cm panchromatic and 168 cm multispectral; and
- WorldView-3 (2014-Present): 34 cm panchromatic and 136 cm multispectral.

Data processing and access:
The Polar Geospatial Center (http://www.pgc.umn.edu/) makes Level 1b and orthorectified imagery available to federally researchers. Derivative products from the imagery, such as DEMs, are freely distributed. Uncorrected DEMs have a vertical accuracy of <5 m; corrected DEMs have a relative accuracy of <1 m.

Contact:
Paul Morin, Polar Geospatial Center (lpaul@umn.edu)
David Shean, University of Washington (dshean@apl.washington.edu)

http://www.pgc.umn.edu/
http://www.pgc.umn.edu/elevation/stereo



(Photos: Morin & Shean)

Satellite Magnetometers and Gradiometers

Satellite magnetic missions are designed to measure the magnetic signals that stem from Earth's core, mantle, crust, oceans, ionosphere and magnetosphere.

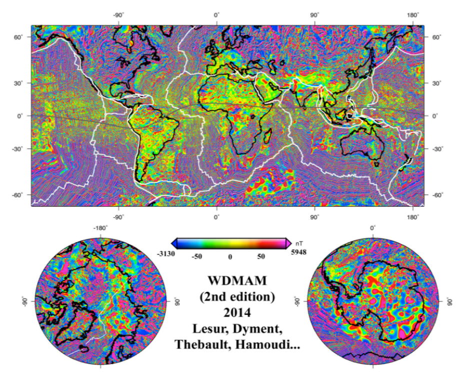
Applications:
Crustal geology, structure, and tectonics; crustal thickness; heat flux; and impact characterization.

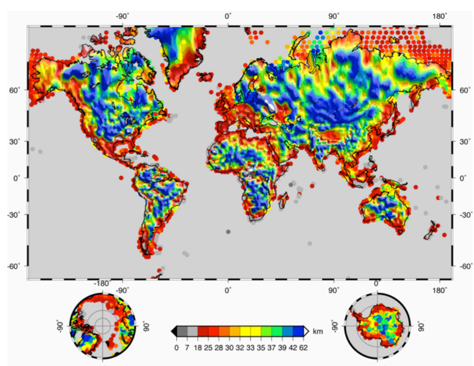
Sensors:
Magsat (1979-1980); Ørsted (1999-Present); CHARM (2000-2012); and Swarm (Alpha, Bravo, and Charlie) (2013-Present).

Data processing and access:
Swarm data is available to registered users on the ESA website (https://earth.esa.int/web/guest/home).

Contact:
Michael Purucker, SGT and NASA (michael.e.purucker@nasa.gov)

Maule, Purucker, Olsen, & Mosegaard (2005). Heat flux anomalies in Antarctica revealed by satellite magnetic data. Science, 309(5733), 464-467.




(Photos: Purucker)

Planetary seismometers

Planetary researchers are investigating means of studying icy bodies with seismology, in an effort to determine sub-surface morphologies.

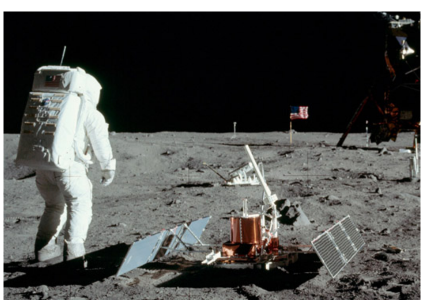
Applications:
Some potential planetary cryosphere targets for seismological studies of ice include the polar caps, ice crusts, and hydrocarbon crusts of various planetary bodies including: Mars; Europa; Enceladus; Titan; Triton; or comets.

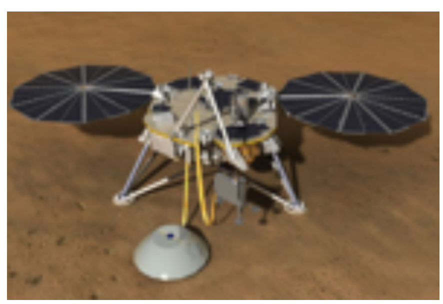
Sensors:
Seismic instrument deployments include: astronaut deployments (e.g., seismology on the moon); robotic landers; penetrators and hard-impactors; and orbital seismology (which will only work without atmosphere). Seismic planetary deployments have included: 5 passive-source instruments on the Moon (Apollo, 1969-1977); 3 active-source instruments on the Moon (Apollo, 1970-1972); 1 instrument on Mars (Viking II, 1976-1980).

Data processing and access:
Planetary seismic data are to be made freely available through IRIS (Incorporated Research Institutions for Seismology) and NASA Planetary Data System (PDS).

Contact:
Nicholas Schmerr, University of Maryland (nschmerr@umd.edu)

Schmerr, Brunt, Cammarano, Hurford, Lekic, Panning, Rhoden, & Sauber (2013). Seismometers on Europa: Insights from Modeling and Antarctic Ice Shelf Analogs. In AGU Fall Meeting Abstracts (Vol. 1, p. 01).





(Photos: Schmerr)